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Atomic data for astrophysics. I. Radiative recombination rates for H-like, He-like, Li-like and Na-like ions over a broad range of temperature

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ABSTRACT

We present new calculations and analytic fits to the rates of radiative recombination towards H-like, He-like, Li-like and Na-like ions of all elements from H through Zn ($Z = 30$). The fits are valid over a wide range of temperature, from 3 K to 10^9 K.

Subject headings: atomic data – atomic processes

1. Introduction

Astrophysical plasmas are generally dilute and far from thermodynamic equilibrium. As a result their physical state and resulting spectra are determined by the balance set by a host of microphysical processes. Total recombination rate coefficients are essential for the prediction of the ionization balance, among other things. Recombination at low densities proceeds through three different physical processes: radiative recombination, $A^{+n} + e^- \rightarrow A^{+n-1} + h\nu$; dielectronic recombination, $A^{+n} + e^- \rightarrow A^{*,+n-1} \rightarrow A^{+n-1} + h\nu$; and charge transfer recombination, $A^{+n} + H^0 \rightarrow A^{+n-1} + H^+$. This paper focuses on radiative recombination for the four isoelectronic sequences where this process should be predominate at nebular ($T \lesssim 10^4$ K) temperatures. Referring to the radiative recombination for an atom/ion, we mean the recombination which forms this species. E.g., "radiative recombination for He I" means the recombination from He II to He I.

During the last two decades, the power-law fits to the radiative recombination rates (Aldrovandi & Pequignot 1973, hereafter AP; Shull & Van Steenberg 1982, Arnaud & Rothenflug 1985, Landini & Monsignori Fossi 1990, 1991) have been extensively used for astrophysical applications. The AP calculations were made for He, C, N, O, Ne, Mg, Si and S. The total radiative recombination coefficient was considered as a sum of recombination coefficients to the ground level and to all the excited levels. The ground level recombination coefficients were evaluated by use of the Milne relation (see, e.g., Bates & Dalgarno 1962) from the photoionization cross sections known in early seventies; for many species, extrapolations of the cross sections along isoelectronic sequences were necessary due to lack of data. For all the excited levels, the hydrogenic approximation was assumed. The calculated radiative recombination coefficients were fitted by

$$\alpha_{\rm r}(T) = A\left(\frac{T}{10^4\ {\rm K}}\right)^{-\eta}, \qquad (1)$$

where T is temperature, A and η are the fitting parameters. Shull & Van Steenberg (1982) calculated and fitted by formula (1) the radiative recombination rates for all Fe ions. They also interpolated the rate coefficients for Ar, Ca and Ni. Interpolations of the rates for Al, Na, F, P, Cl, K, Ti, Cr, Mn and Co were done by Landini & Monsignori Fossi (1990, 1991). Arnaud & Rothenflug (1985) improved the AP and Shull & Van Steenberg (1982) rates for recombination towards He-like, Li-like and Be-like ions, using the same power-law fitting formula (1).

Gould (1978) introduced corrections to the hydrogenic formula for the radiative recombination coefficients to the excited levels of nonhydrogenic species. He provided more accurate total radiative recombination coefficients for the first four ionization states of C, N, O, Ne, Mg, Si, S, Ar at $T = 10^4$ K, and for the neutral species of these elements at $T = 10^2$ K. Pequignot, Petitjean, & Boisson (1991) used updated photoionization cross sections from the ground and first excited ($n = 2$ and $n = 3$) states of all ions of He, C, N, O, and Ne for calculation of the radiative recombination coefficients. All levels $n > 3$ were assumed to be hydrogenic. The results were fitted by the 4-parametric formula

$$\alpha_{\rm r}(T) = 10^{-13} z \frac{at^b}{1+ct^d}\ {\rm cm^3 s^{-1}}, \qquad (2)$$

where z is the ionic charge ($z = 1$ for recombination towards neutral state), $t = 10^{-4}T/z^2$, and a, b, c, and d are the fitting parameters. These fits are valid for the temperature range $40z^2 \leq T \leq 4 \times 10^4 z^2$ K. Arnaud & Raymond (1992) calculated iron radiative recombination rates of Fe XV through Fe XXVI using the photoionization cross sections from the ground and all the excited states with $n \leq 5$ presented by Clark, Cowan, & Bobrowicz (1986). The rates coefficients were fitted by a modified form of Eq. (1);

$$\alpha_{\rm r}(T) = A\left(\frac{T}{10^4\ {\rm K}}\right)^{-\alpha-\beta\log_{10}(T/10^4\ {\rm K})}, \qquad (3)$$

where A, α and β are the fitting parameters.

This paper is part of a series concerned with the basic data needed to fully simulate spectral formation by all stages of ionization of the first thirty elements. Reliable rates are needed over the full temperature range 3 K $\leq T \leq 10^9$ K. During the last years, new extensive calculations of the photoionization cross sections have been performed and published. Verner & Yakovlev (1995) presented a complete set of analytic fits to the partial Hartree-Dirac-Slater (HDS) photoionization cross sections for the ground state shells of all atoms and ions of elements from H to Zn. These fits are very accurate far from the ionization thresholds of the outer shells and at higher energies above the subsequent inner shell ionization edges. However, the HDS method may give significant errors near the thresholds of the outer shells, especially for neutral and low-ionized species. Use of the fits to the HDS photoionization cross sections for evaluation of the radiative recombination rates may lead to large errors in the low-temperature rates for neutral and low-ionized species. The recent Opacity Project (OP) calculations (Seaton et al. 1992) give more accurate low-energy photoionization cross sections obtained by the R-matrix method (Burke et al. 1971) for all atoms and ions of elements with $Z \leq 14$ and $Z = 16, 18, 20, 26$ (Z is atomic number). Unfortunately the OP calculations do not include high-energy photoionization cross sections; these are required for high-temperature radiative recombination rates. Moreover, the OP database TOPbase (Cunto et al. 1993) contains only total photoionization cross sections which are not appropriate for use with the Milne relation.

For the most ionic species, the total recombination rates are dominated by dielectronic recombination (Burgess 1964; Nussbaumer & Storey 1984, 1986, 1987). The exceptions are H-like ions which are not subject to dielectronic recombination at all, and He-like, Li-like and Na-like species which do not have low-lying autoionization states and therefore are not subject to low-temperature dielectronic recombination (the process discussed in the papers by Nussbamer & Storey). Thus, the rates of radiative recombination towards He-like, Li-like and Na-like ions described here should be the total recombination rate at nebular temperatures, and only need to be supplemented by high-temperature dielectronic recombination.

2. Calculations and fits

In this paper, we present the calculations and analytic fits to the rates of radiative recombination towards H-like, He-like, Li-like and Na-like ions of all elements from H through Zn ($Z = 30$). For calculation of the ground level recombination rate coefficients for He-like, Li-like and Na-like ions, we used the updated version of the analytic fits to the photoionization cross sections (Verner et al. 1995) which give the corrected threshold cross sections and near-threshold cross section behavior based on the OP data, and ensure accurate high energy cross sections by use of the fitting formula with the correct non-relativistic asymptote. At high temperatures, the direct recombination to the ground state gives the largest contribution to the total radiative recombination rate coefficient.

For calculation of the rate coefficients to the excited levels with $n \leq 5$ of the five and more times ionized species, we used Clark et al. (1986) fits to the partial photoionization cross sections. Note that the formula given by Clark et al. (1986) fits the cross sections up to $10E_{\rm th}$ only, where $E_{\rm th}$ is the ionization threshold energy, and does not ensure correct asymptotic behavior: the cross sections decrease too slowly with increasing energy. It leads to artificially too high recombination rate coefficients for Na-like species at $T \sim 10^8$ K. To avoid it, we substituted Clark et al. high energy tails by fits $\propto E^{-3}$ from $10E_{\rm th}$ to $100E_{\rm th}$, and by non-relativistic asymptote $\propto E^{-3.5-l}$, where l is a subshell orbital quantum number, above $100E_{\rm th}$. This substitute changes the high-temperature rates for He-like and Li-like ions by less than 1% but improves the rate coefficients for Na-like species at $T \gtrsim 10^8$ K.

For calculation of the radiative recombination rates to the excited levels with $n \leq 10$ of the first four ionization states where Clark et al. (1986) fits are not valid, we used the Gould (1978) method of correction for incomplete shielding. The required values of energy levels with $n \leq 10$ for He I, Li I, Li II, Be II, Be III, B III,B IV, C IV, Na I, Mg II, Al III, Si IV were retrieved from the TOPbase 0.7 (Cunto et al. 1993). We used the hydrogenic approximation for levels with $n > 10$ (the species listed above) and for levels with $n > 5$ (five and more times ionized species).

To estimate uncertainty of the Gould method, we have made more detailed calculations of the radiative recombination rates for He I. This is motivated by the importance of this process in measurements of the primordial helium abundance (Reeves 1992). We used the OP He I partial photoionization cross sections (Fernley, Taylor, & Seaton 1987) of 40 low-lying excited levels with $n < 10$ ($l < 3$; ^1S, $^1P^o$, ^1D, ^3S, $^3P^o$, and ^3D levels) to obtain recombination rates to these levels. All levels with $n \geq 10$ were assumed hydrogenic. Then we compared the obtained total radiative recombination rates with those calculated by the Gould method. At $T \leq 10^2$ K, the discrepancies between these two methods are less than 1%, since the main contribution to the total rate at these temperatures comes from the recombination to highly excited hydrogenic levels. At $T > 10^2$ K, the discrepancies begin to increase with increasing temperature, and reach a maximum of 10% at $T = 10^5$ K. At higher T, the discrepancies decrease again, since the main contribution to the total rate at high temperature comes from the ground state recombination. Thus, we can estimate that the accuracy of the Gould method is not worse than 10%. The comparison of experimental and fitted photoionization cross sections of neutrals (He, Li, Na) reveal that the accuracy of the fits to the ground state photoionization cross sections is better than 10% also. Therefore, the absolute accuracy of the calculated total radiative recombination rates presented here is not worse than 10% for neutrals, and must be better for ions.

Careful integration of the Milne relation and use of the photoionization cross sections which are accurate as near the thresholds as at high energies ensure the high accuracy of the total recombination rate coefficients in a wide range of temperature. We calculated all the rates from 3 K to 10^{10} K using non-relativistic photoionization cross sections. However, at temperatures above 10^8 K, relativistic corrections may be important for high-Z ions. As we have mentioned, the largest contribution to the total recombination at $T > 10^8$ K comes from the recombination to the ground level. Our fits for the ground level photoionization cross sections of H and He agree within 2% with the experimental cross sections (Veigele 1973) at energies up to 1 MeV. Thus, the given recombination rates coefficients are accurate at temperatures up to 10^9 K for low-Z ions. For high-Z ions, $T = 10^8$ K is more secure upper limit.

We fitted all the total rate coefficients obtained in the temperature range from 3 K to 10^{10} K using the formula

$$\alpha_{\rm r}(T) = a\left[\sqrt{T/T_0}\left(1+\sqrt{T/T_0}\right)^{1-b}\left(1+\sqrt{T/T_1}\right)^{1+b}\right]^{-1}, \tag{4}$$

where a, b, T_0 and T_1 are the fitting parameters. Formula (4) ensures correct asymptotic behavior of the rate coefficients (Ferland et al. 1992) as at low as at high temperatures: $\alpha_{\rm r}(T) \propto T^{-0.5}$ at $T \ll T_0 \ll T_1$, and $\alpha_{\rm r}(T) \propto T^{-1.5}$ at $T \gg T_1 \gg T_0$. The average accuracy of fitting is better than 2% (maximum error is less than 3%) for He-like ions and better than 4% (maximum error is less than 6%) for all Li-like and Na-like species. The errors of fitting are smaller for highly-ionized species. Note that although all the fits are accurate in comparison with the calculated data up to 10^{10} K, the upper limits of validity (10^8 K for high-Z ions, and 10^9 K for low-Z ions) are determined by non-relativistic character of the calculations.

Because of its importance for cosmological problems, we present two fits for the He I rates which are calculated by more detailed method (see above). The first fit is valid at $T \leq 10^6$ K (the rms average error is 2.5%, maximum error 5%). Note that the He I high-temperature dielectronic recombination rate at $T = 10^6$ K is two orders of magnitude larger than the radiative recombination rate at this temperature. The second fit is valid for all temperatures from $T = 3$ K up to $T = 10^{10}$ K (the rms average error is 5%, maximum error 10%). The errors of fitting for all species under study are not higher than the estimated absolute errors. Therefore, our fitting does not lead to any loss of accuracy in comparison with the calculated data.

We also fitted the recombination rate coefficients for all the H-like ions. Generally, the rate coefficients for all hydrogenic species can be obtained from the H I rate coefficient by use of the relation

$$\alpha_{\rm r}(Z,T) = Z\alpha_{\rm r}(1, T/Z^2). \tag{5}$$

However, for user's convenience we provide the separate fits to all the hydrogenic species which ensure the uniform accuracy of the fitting for all ions in the same temperature range 3 K–10^{10} K. The rms relative errors of the fits for all hydrogenic species are less than 0.5%, the maximum errors are less than 1%.

The fit parameters are listed in Table 1. We have made extensive comparisons of our fits with the fits provided by AP, Shull & Van Steenberg (1982), Arnaud & Rothenflug (1985), Landini & Monsignori Fossi (1990, 1991), Pequignot et al. (1991) and Arnaud & Raymond (1992). Our fits are in a very good agreement with the fits by Pequignot et al. (1991) and Arnaud & Raymond (1992) in the temperature range where the previous fits are valid. Our fits are accurate in a much wider temperature range, however, since our fitting formula has correct low-temperature and high-temperature asymptotes. The agreement with AP, Shull & Van Steenberg (1982), Arnaud & Rothenflug (1985) and Landini & Monsignori Fossi (1990, 1991) is worse, especially for the cases interpolated along isoelectronic sequences in earlier papers . Figures 1–6 illustrate the comparison for helium-like ions O VII and Si XIII, lithium-like ions C IV and Fe XXIV, and sodium-like ions Mg II and Ca X. In Table 2, we compare the rates given by our fits with the rates provided by

Gould (1978) at $T = 10^4$ K for the three species which we have in common. The rates for these species obtained from the previously available fits are also shown.

For the hydrogenic species, Arnaud & Rothenflug (1985) recommended the formula given by Seaton (1959):

$$\alpha_{\rm r}(Z,T) = 5.197 \times 10^{-14} Z\lambda^{1/2}[0.4288 + 0.5\ln(\lambda) + 0.469\lambda^{-1/3}], \tag{6}$$

where $\lambda = 157890Z^2/T$ (K). However, this formula is not valid at high ($T > 10^6 Z^2$) temperatures. The hydrogenic fit given by Pequignot et al. (1991) also has incorrect high-temperature asymptote. Figures 7 and 8 compare our hydrogenic data and fits with the previously available fits.

It can be useful for astrophysical applications to separate the partial recombination rate to the ground state and the recombination rate to all the excited states. We have fitted the rates of radiative recombination to the ground states and the rates of radiative recombination to all the excited states by the same fitting formula (4). The corresponding fit parameters are available from the authors upon request. The accuracy of fitting of the partial rate coefficients is generally slightly lower than that of the total radiative recombination rates coefficients.

3. Discussion

Our long-term goal is to predict the complete spectrum emitted by the first 30 elements. Fits to the needed photoionization cross sections are presented by Verner & Yakovlev (1995) and Verner et al. (1995). Here we present accurate fits to the total radiative recombination rates for 107 ions of 4 isoelectronic sequences, 23% of the rate coefficients needed for the 465 possible ions of the first 30 elements. This is the complete set of species for which simple radiative recombination is expected to be the dominant channel at nebular temperatures.

Our temperature range was selected with astrophysical needs in mind. We briefly mention two cases, at either temperature extreme, where the results presented here affect published results. In the low T extreme, charge transfer with He^+ is the dominant CO destruction mechanism in photodissociation regions (PDRs) for most conditions (Tielens & Hollenbach 1985, Hollenbach & McKee 1989, Ferland, Fabian, & Johnstone 1994). The He^+ abundance is set by the balance between creation mechanisms (often ionization by cosmic rays or X-Rays) and radiative recombination. Our total rate coefficient for radiative recombination of He^+ to He at 300 K, a representative PDR temperature, is 4.43×10^{-12} cm^{3}s^{-1}. This is 25% larger than the rate used by Hollenbach & McKee (1989). Tests show that this does indeed result in a substantially greater CO abundance and cooling. At the opposite temperature extreme, heating by photoionization of hydrogenic species of the heavy elements is the main heating mechanism for a gas near 10^6 K. Our rates are often quite different from the power-law fits (AP, Shull & Van Steenberg 1982, Arnaud

& Rothenflug 1985) extrapolated to high temperatures, and tests show that the photoelectric heating and resulting electron temperature tend to be lower, by as much as 20%.

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TABLE 1

Fit parameters for radiative recombination rates

Ion	Z	N	a, cm^3s^{-1}	b	T_0, K	T_1, K
H I	1	1	7.982e−11	0.7480	3.148e+00	7.036e+05
He I [a]	2	2	3.294e−11	0.6910	1.554e+01	3.676e+07
He I [b]	2	2	9.356e−10	0.7892	4.266e−02	4.677e+06
He II	2	1	1.891e−10	0.7524	9.370e+00	2.774e+06
Li I	3	3	1.036e−11	0.3880	1.077e+02	1.177e+07
Li II	3	2	1.112e−10	0.6926	2.437e+01	8.323e+06
Li III	3	1	3.039e−10	0.7539	1.871e+01	6.209e+06
Be II	4	3	2.338e−11	0.4211	3.647e+02	1.215e+07
Be III	4	2	1.317e−10	0.6691	8.473e+01	1.412e+07
Be IV	4	1	4.290e−10	0.7557	3.000e+01	1.093e+07
B III	5	3	4.487e−11	0.4644	5.371e+02	1.465e+07
B IV	5	2	1.922e−10	0.6717	1.272e+02	1.975e+07
B V	5	1	5.437e−10	0.7560	4.576e+01	1.706e+07
C IV	6	3	8.540e−11	0.5247	5.014e+02	1.479e+07
C V	6	2	2.765e−10	0.6858	1.535e+02	2.556e+07
C VI	6	1	6.556e−10	0.7567	6.523e+01	2.446e+07
N V	7	3	1.169e−10	0.5470	6.793e+02	1.650e+07
N VI	7	2	3.910e−10	0.6988	1.611e+02	3.271e+07
N VII	7	1	7.586e−10	0.7563	9.015e+01	3.338e+07
O VI	8	3	2.053e−10	0.6019	4.772e+02	1.711e+07
O VII	8	2	4.897e−10	0.7048	1.906e+02	4.093e+07
O VIII	8	1	8.616e−10	0.7563	1.191e+02	4.352e+07
F VII	9	3	2.739e−10	0.6188	5.033e+02	2.064e+07
F VIII	9	2	5.602e−10	0.7052	2.476e+02	5.077e+07
F IX	9	1	9.712e−10	0.7566	1.499e+02	5.498e+07
Ne VIII	10	3	3.200e−10	0.6198	6.329e+02	2.616e+07
Ne IX	10	2	6.161e−10	0.7029	3.274e+02	6.243e+07
Ne X	10	1	1.085e−09	0.7570	1.834e+02	6.776e+07
Na I	11	11	5.641e−12	0.1749	3.077e+02	2.617e+06
Na IX	11	3	3.873e−10	0.6295	7.000e+02	2.989e+07
Na X	11	2	6.833e−10	0.7018	4.060e+02	7.491e+07
Na XI	11	1	1.163e−09	0.7558	2.328e+02	8.262e+07
Mg II	12	11	1.920e−11	0.3028	4.849e+02	5.890e+06
Mg X	12	3	4.284e−10	0.6287	8.748e+02	3.586e+07
Mg XI	12	2	7.510e−10	0.7020	4.921e+02	8.643e+07
Mg XII	12	1	1.317e−09	0.7574	2.585e+02	9.769e+07
Al III	13	11	3.753e−11	0.3585	6.848e+02	9.035e+06
Al XI	13	3	4.881e−10	0.6326	9.941e+02	4.085e+07
Al XII	13	2	8.182e−10	0.7008	5.875e+02	1.007e+08
Al XIII	13	1	1.419e−09	0.7578	3.057e+02	1.143e+08
Si IV	14	11	5.942e−11	0.3930	8.962e+02	1.213e+07
Si XII	14	3	5.373e−10	0.6337	1.164e+03	4.677e+07
Si XIII	14	2	8.722e−10	0.6996	7.098e+02	1.155e+08
Si XIV	14	1	1.517e−09	0.7574	3.601e+02	1.329e+08
P V	15	11	1.721e−10	0.5429	2.848e+02	3.975e+07
P XIII	15	3	5.876e−10	0.6354	1.341e+03	5.292e+07
P XIV	15	2	9.142e−10	0.6961	8.682e+02	1.335e+08
P XV	15	1	1.586e−09	0.7560	4.327e+02	1.534e+08
S VI	16	11	3.502e−10	0.6266	1.532e+02	1.755e+07
S XIV	16	3	6.571e−10	0.6400	1.452e+03	5.796e+07
S XV	16	2	9.692e−10	0.6945	1.017e+03	1.517e+08
S XVI	16	1	1.729e−09	0.7568	4.725e+02	1.746e+08
Cl VII	17	11	2.502e−10	0.5580	5.303e+02	4.558e+07
Cl XV	17	3	7.076e−10	0.6397	1.653e+03	6.555e+07
Cl XVI	17	2	1.021e−09	0.6932	1.184e+03	1.695e+08
Cl XVII	17	1	1.791e−09	0.7565	5.591e+02	1.972e+08
Ar VIII	18	11	2.862e−10	0.5621	7.002e+02	4.885e+07
Ar XVI	18	3	7.538e−10	0.6388	1.889e+03	7.306e+07
Ar XVII	18	2	1.087e−09	0.6936	1.329e+03	1.880e+08
Ar XVIII	18	1	1.913e−09	0.7567	6.175e+02	2.212e+08

TABLE 1—*Continued*

Ion	Z	N	a, cm^3s^{-1}	b	T_0, K	T_1, K
K IX	19	11	2.757e−10	0.5364	1.204e+03	7.013e+07
K XVII	19	3	8.182e−10	0.6411	2.044e+03	8.057e+07
K XVIII	19	2	1.145e−09	0.6921	1.503e+03	2.098e+08
K XIX	19	1	2.033e−09	0.7569	6.797e+02	2.463e+08
Ca X	20	11	5.273e−10	0.6281	5.329e+02	3.188e+07
Ca XVIII	20	3	8.577e−10	0.6403	2.334e+03	8.850e+07
Ca XIX	20	2	1.179e−09	0.6893	1.757e+03	2.344e+08
Ca XX	20	1	2.129e−09	0.7570	7.591e+02	2.739e+08
Sc XI	21	11	3.890e−10	0.5645	1.391e+03	6.295e+07
Sc XIX	21	3	9.162e−10	0.6413	2.543e+03	9.690e+07
Sc XX	21	2	1.265e−09	0.6902	1.877e+03	2.555e+08
Sc XXI	21	1	2.262e−09	0.7578	8.186e+02	3.000e+08
Ti XII	22	11	4.207e−10	0.5646	1.688e+03	6.872e+07
Ti XX	22	3	9.844e−10	0.6440	2.708e+03	1.044e+08
Ti XXI	22	2	1.322e−09	0.6885	2.092e+03	2.829e+08
Ti XXII	22	1	2.370e−09	0.7574	9.002e+02	3.307e+08
V XIII	23	11	4.605e−10	0.5659	1.949e+03	7.419e+07
V XXI	23	3	1.020e−09	0.6427	3.057e+03	1.140e+08
V XXII	23	2	1.375e−09	0.6885	2.321e+03	3.056e+08
V XXIII	23	1	2.415e−09	0.7565	1.032e+03	3.635e+08
Cr XIV	24	11	4.975e−10	0.5655	2.257e+03	8.072e+07
Cr XXII	24	3	1.091e−09	0.6445	3.225e+03	1.229e+08
Cr XXIII	24	2	1.422e−09	0.6874	2.589e+03	3.336e+08
Cr XXIV	24	1	2.537e−09	0.7571	1.108e+03	3.954e+08
Mn XV	25	11	5.349e−10	0.5658	2.577e+03	8.710e+07
Mn XXIII	25	3	1.151e−09	0.6451	3.461e+03	1.334e+08
Mn XXIV	25	2	1.488e−09	0.6867	2.802e+03	3.623e+08
Mn XXV	25	1	2.618e−09	0.7565	1.225e+03	4.307e+08
Fe XVI	26	11	7.688e−10	0.6173	1.653e+03	6.161e+07
Fe XXIV	26	3	1.198e−09	0.6443	3.789e+03	1.437e+08
Fe XXV	26	2	1.542e−09	0.6859	3.073e+03	3.926e+08
Fe XXVI	26	1	2.735e−09	0.7568	1.314e+03	4.659e+08
Co XVII	27	11	5.850e−10	0.5598	3.538e+03	1.052e+08
Co XXV	27	3	1.211e−09	0.6406	4.357e+03	1.572e+08
Co XXVI	27	2	1.589e−09	0.6846	3.373e+03	4.267e+08
Co XXVII	27	1	2.809e−09	0.7565	1.444e+03	5.042e+08
Ni XVIII	28	11	6.347e−10	0.5631	3.780e+03	1.116e+08
Ni XXVI	28	3	1.288e−09	0.6440	4.506e+03	1.651e+08
Ni XXVII	28	2	1.676e−09	0.6861	3.530e+03	4.538e+08
Ni XXVIII	28	1	3.002e−09	0.7581	1.467e+03	5.409e+08
Cu XIX	29	11	6.619e−10	0.5602	4.322e+03	1.210e+08
Cu XXVII	29	3	1.372e−09	0.6472	4.627e+03	1.740e+08
Cu XXVIII	29	2	1.686e−09	0.6824	4.031e+03	4.948e+08
Cu XXIX	29	1	3.022e−09	0.7564	1.666e+03	5.855e+08
Zn XX	30	11	7.002e−10	0.5612	4.726e+03	1.287e+08
Zn XXVIII	30	3	1.412e−09	0.6454	5.053e+03	1.891e+08
Zn XXIX	30	2	1.758e−09	0.6834	4.254e+03	5.258e+08
Zn XXX	30	1	3.127e−09	0.7567	1.779e+03	6.246e+08

[a]Fit is valid at 3 K $\leq T \leq 10^6$ K, rms error 2.5%
[b]Fit is valid at 3 K $\leq T \leq 10^{10}$ K, rms error 4.7%

TABLE 2

RADIATIVE RECOMBINATION COEFFICIENTS (IN $cm^3 s^{-1}$) AT $T = 10^4$ K

Ion	Gould (1978)	Present fit	Old fits [a]
C IV	8.45×10^{-12}	8.20×10^{-12}	9.16×10^{-12}
Mg II	1.35×10^{-12}	1.22×10^{-12}	8.8×10^{-13}
Si IV	7.32×10^{-12}	7.02×10^{-12}	5.5×10^{-12}

[a]Arnaud & Rothenflug (1985) for C IV, Aldrovandi & Pequignot (1973) for Mg II and Si IV

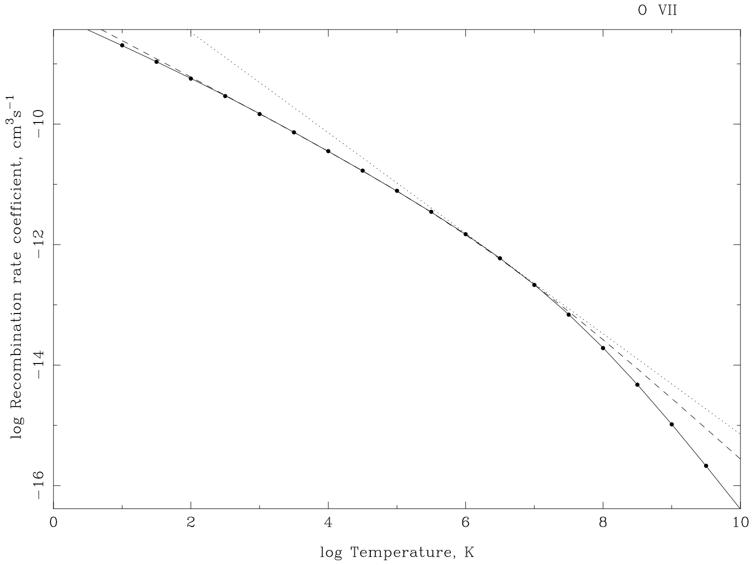

Fig. 1.— Radiative recombination rate coefficient of O VII vs. temperature. *Circles:* present calculations; *solid line:* present fit; *dotted line:* Arnaud & Rothenflug (1985); *dashed line:* Pequignot et al. (1991).

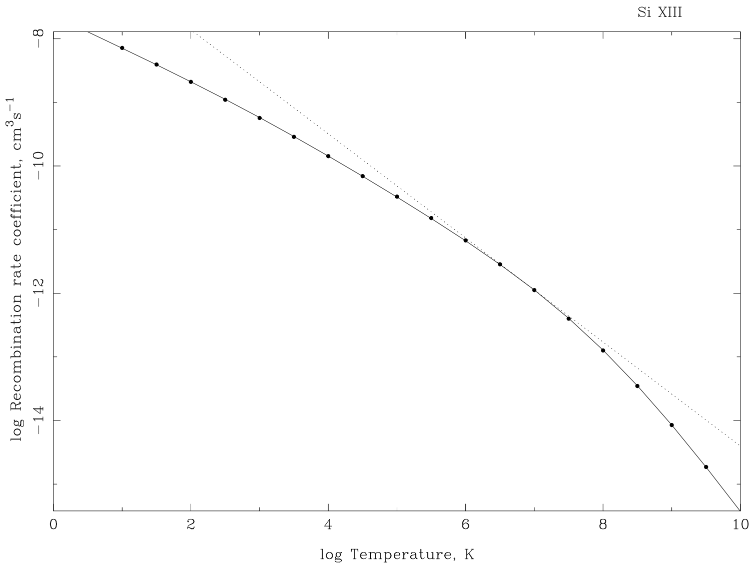

Fig. 2.— Same as Fig. 1 for Si XIII.

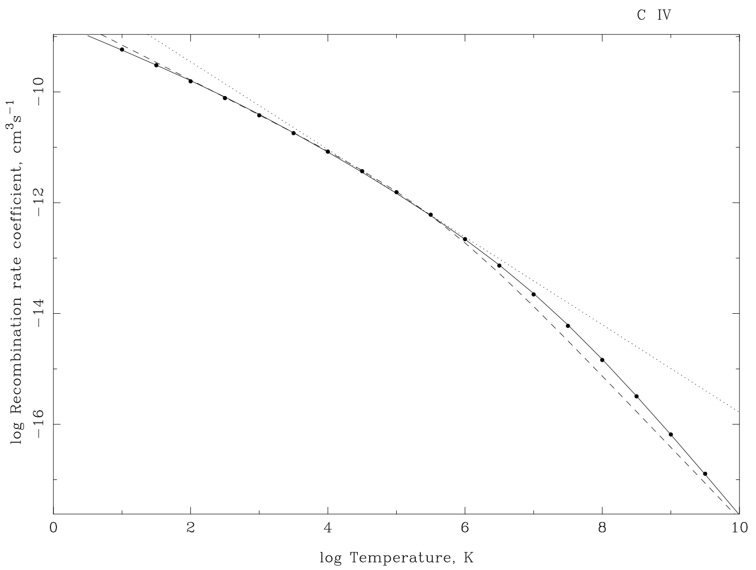

Fig. 3.— Same as Fig. 1 for C IV.

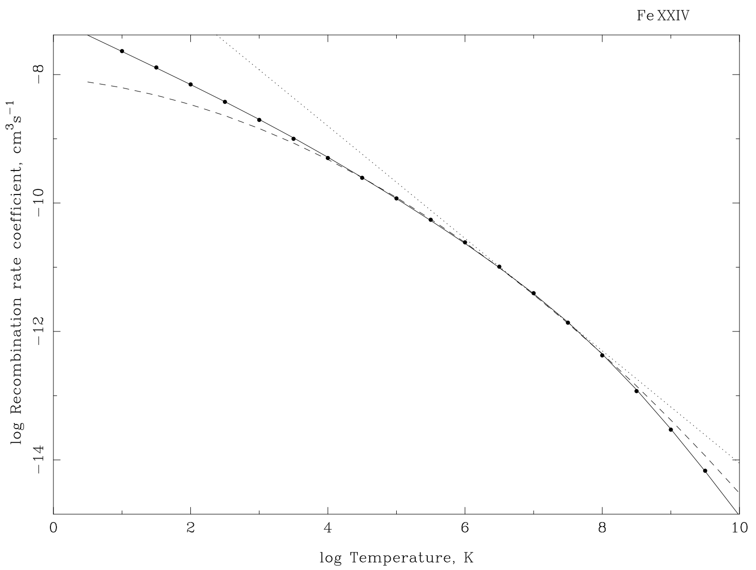

Fig. 4.— Same as Fig. 1 for Fe XXIV. *Dashed line:* Arnaud & Raymond (1992).

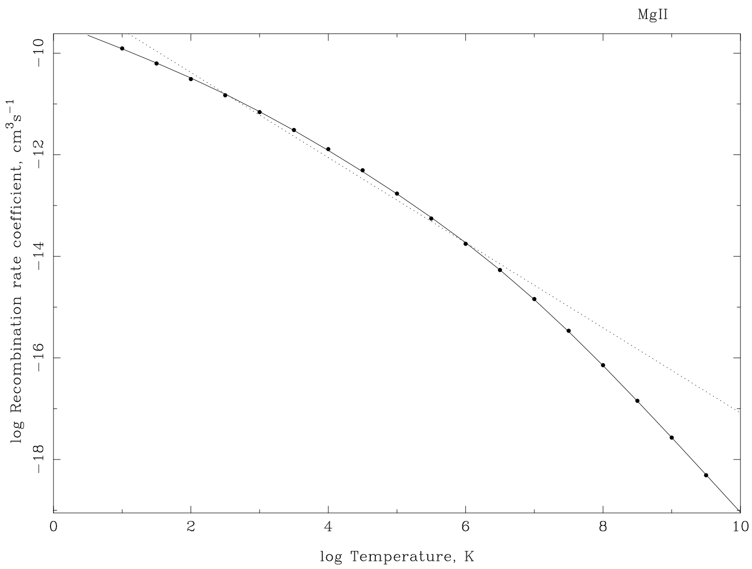

Fig. 5.— Same as Fig. 1 for Mg II. *Dotted line:* Aldrovandi & Pequignot (1973).

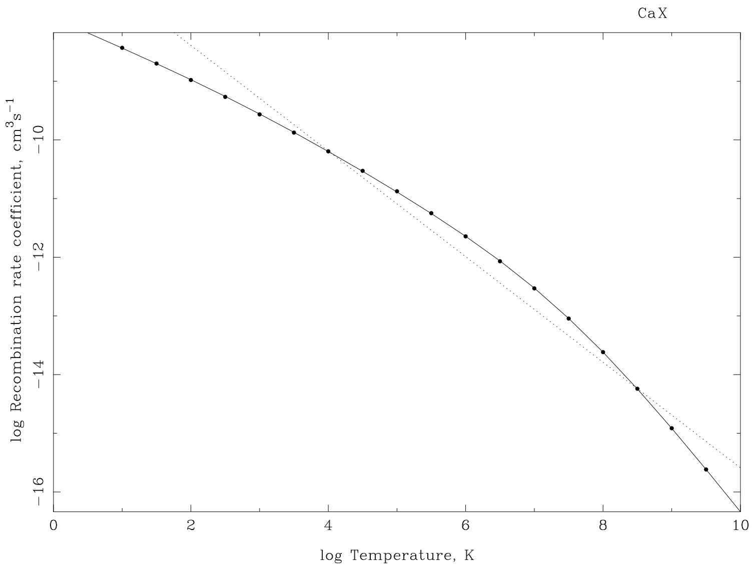

Fig. 6.— Same as Fig. 1 for Ca X. *Dotted line:* Shull & Van Steenberg (1982).

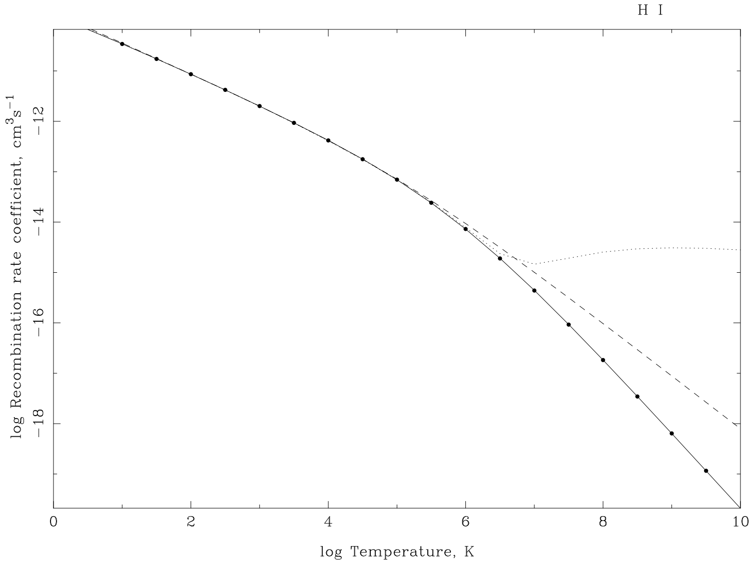

Fig. 7.— Radiative recombination rate coefficient of H I vs. temperature. *Circles:* present calculations; *solid line:* present fit; *dotted line:* Seaton (1959); *dashed line:* Pequignot et al. (1991).

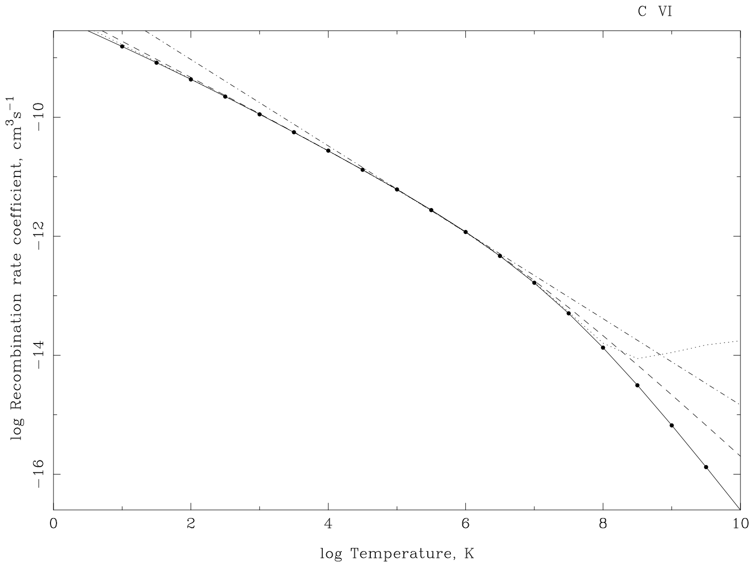

Fig. 8.— Same as Fig. 7 for C VI. *Dash-dotted line:* Shull & Van Steenberg (1982, see also erratum).